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This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/120216> since

Published version:

DOI:10.1080/17445647.2012.744367

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This is an author version of the contribution published on:

Questa è la versione dell'autore dell'opera:

Compagnoni R., Rolfo F., Groppo C., Hirajima T. & Turello R. (2012). Geological map of the Ultra-High Pressure Brossasco-Isasca Unit (Western Alps, Italy). Journal of Maps, 8 (4), 465-472, doi: 10.1080/17445647.2012.744367

The definitive version is available at:

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<http://www.tandfonline.com/doi/full/10.1080/17445647.2012.744367#.UxyYCYVm2ul>

GEOLOGICAL MAP OF THE ULTRA-HIGH PRESSURE BROSSASCO-ISASCA UNIT (WESTERN ALPS, ITALY)

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Abstract

In the southern Dora-Maira Massif, Western Alps, slivers of continental crust with similar lithologies, but recrystallised during the Alpine orogeny at different peak-*P* conditions, are exposed. They include the Brossasco-Isasca Unit (BIU) where coesite was first discovered in continental crust (Chopin, 1984).

A new 1:20,000-scale geologic map and related cross-sections of the whole BIU and adjoining units is presented, in which the most significant features useful to infer the pre-Alpine history and the Alpine tectonic and metamorphic evolution, are summarized. Thanks to detailed petrography and petrology, the geologic map shows the precise location of ultra-high pressure (UHP) minerals (such as coesite), and the locations of the most significant mineral assemblages (such as kyanite + jadeite). This innovative approach is used to distinguish the BIU from the adjacent units. Relict pre-Alpine structures (such as igneous intrusive contacts with basement xenoliths and metagranitoids) are summarised in a sketch illustrating the geologic setting of the UHP metamorphic unit as inferred before the Alpine orogeny.

Key words: ultra-high pressure metamorphism (UHPM), Dora-Maira Massif, Western Alps.

Introduction

The Dora-Maira Massif (DMM) extends from Val di Susa (to the north) to Val Maira (to the south) for a length of about 70 km from north to south and an average width of about 25 km from east to west. The DMM together with the Monte Rosa and Gran Paradiso massifs are known as the Internal Crystalline Massifs of the Penninic Domain of the western Alps.

The DMM consists of a composite ensemble of nappes, and traditionally includes three main lithotectonic units formed by a number of tectonic slices (Vialon, 1966) which are (from west to east, and from upper to lower structural levels): 1) the upper Dronero-Sampeyre Unit, 2) the intermediate Polymetamorphic unit, and 3) the lower Pinerolo unit. A revision of the DMM lithotectonic architecture has been done by Sandrone et al. (1993).

After the discovery of coesite (Chopin, 1984) in the southern sector of the intermediate Polymetamorphic unit of Vialon (1966), the scientific interest for the southern DMM increased rapidly and a number of detailed petrologic studies have been produced (e.g., Chopin et al., 1991; Schertl et al., 1991; Compagnoni et al., 1995; Michard et al., 1995; Chopin & Schertl, 2000; Nowlan et al., 2000; Compagnoni & Hirajima, 2001; Groppo et al., 2006; Castelli et al., 2007; Groppo et al., 2007a, b; Ferrando et al., 2009) aimed to determine its peak metamorphic conditions. The UHP unit has also been mapped in great detail, and special attention has been paid to recognize the relics of both pre-Alpine and early-Alpine structures and minerals which are essential to understand nature and relationships among lithologies and to check the internal coherency of the unit.

After the geologic map of Compagnoni et al. (2004), new field data led to define the exact extension of the UHP unit, named Brossasco-Isasca Unit (BIU). As a fundamental contribution of petrology to field mapping, it has been recognized that most crystalline units exposed in the area, though deriving from a same Variscan amphibolite-facies basement intruded by Permian granitoids, were characterized by different early-Alpine high-*P* peak metamorphic overprints, ranging from the epidote-blueschist to the coesite-eclogite-facies conditions (e.g., Chopin et al., 1991; Compagnoni & Rolfo, 2003). The coesite-eclogite bearing BIU is ca. 10 km long, 4 km wide and less than 1 km thick, and is tectonically sandwiched between two quartz-eclogite units, in turn surrounded by two units with early-Alpine epidote blueschist facies overprint (see Insert B in the Geologic Map). The early Alpine HP to UHP metamorphic peak is in turn overprinted by a late Alpine pervasive greenschist facies recrystallization that extensively obliterated the previous HP mineral assemblages and reworked almost all tectonic contacts and shear zones, producing a plethora of contrasting kinematic indicators.

Methods

The mapped area occurs in a vegetated land which extends between ca. 500 and 1500 m a.s.l. Excluding a few main bodies of augen gneiss that make steep and continuous walls, most lithologies have a limited exposure of about 15-20%. However, thanks to the relatively homogeneous outcrop distribution and the constancy of the attitude of the main rock compositional layering and composite metamorphic foliations and shear zones, a reliable interpretative geologic map was produced.

The outcrop map was originally mapped at the 1:10,000 scale. Both the original data and the map are represented on a raster topographic map at the 1:25,000 scale (maps of the IGM, tavolette: 079 I-NO Sanfront, 079 I-NE Revello, 07- I-SO Melle and 079 I-SE Venasca). Because of its high scientific interest, a special attention has been paid to the mapping of the UHP BIU. For the sake of

clarity, in the interpretative geologic map both *eluvium* and *colluvium* deposits, covering more than 70% of the area, have been omitted. Part of this map, devoid of its eastern termination, has been published in a special volume edited in occasion of the International Geological Congress held in Florence in 2004 (Compagnoni et al., 2004).

The main problem to define the real extension of the UHP BIU arises from the fact that the underlying San Chiaffredo unit and the overlying Rocca Solei unit (described later on) derive from the same pre-Alpine basement and include large bodies of orthogneiss derived from late Variscan granitoids (Fig. 1) extensively overprinted by late-Alpine greenschist-facies metamorphism, as also observed in the BIU. The distinction between the UHP BIU and the HP adjacent units is therefore very difficult to determine in the field.

Our study has shown that a distinction between several tectonometamorphic units recrystallized at different HP conditions is only possible if the geologic survey is coupled with a close net of sampling and a detailed petrologic, microstructural and minerochemical study. Consequently, more than 800 samples have been collected (Fig. 2) and the relevant thin sections have been studied by means of the optical polarizing microscope (Fig. 3, 4). A selection of representative samples has been studied at the SEM-EDS (Energy-Dispersive Spectroscopy) and WDS (Wavelength-Dispersive Spectroscopy) and the chemical composition of minerals has been determined with special attention to the mineral zoning and micro-inclusion occurrence. The analytical data have been organized in a database and used to constrain the whole metamorphic evolution of the BIU and adjoining units (see for example the review by Compagnoni & Rolfo, 2003).

Once acquired, the *P-T* data have been used to define the extension of each coherent unit. This approach led to definition of four adjacent tectonometamorphic units, and help to trace their tectonic contacts (see below) that are usually hidden by the poor rock exposure and the strong late-Alpine greenschist-facies overprint.

The nappe pile of southern Dora-Maira Massif

On the basis of geologic and microstructural data, with the essential contribution of petrology, in the mapped area the following four main tectonometamorphic units have been distinguished, from the lower to the upper structural levels:

- 1) The **Pinerolo Unit** consists of prevailing graphitic phengite-gneiss, locally garnet- and chloritoid-bearing, with intercalations of phengite-quartzite and minor garnet-bearing paraschist including lenses of metabasite. The early-Alpine metamorphic peak at epidote-blueschist facies conditions was overprinted by a late-Alpine greenschist-facies recrystallization.
- 2) The **San Chiaffredo Unit** is a portion of a pre-Alpine continental crust similar to the BIU, consisting of a Variscan amphibolite-facies metamorphic basement (now micaschist and eclogite) intruded by Permian granitoids (now fine-grained orthogneiss and augen-gneiss). The early-Alpine metamorphism under quartz-eclogite facies conditions was overprinted by a pervasive late-Alpine greenschist-facies recrystallization.
- 3) The **Brossasco-Isasca Unit (BIU)** consists of a Variscan amphibolite-facies metamorphic basement (now garnet-kyanite micaschist, impure marble and eclogite) intruded by Permian granitoids (Gebauer et al., 1997) (now mainly augen-gneiss and minor metagranite and pyrope-bearing whiteschist: Fig. 2a-b) which produced a contact metamorphic aureole (Fig. 2c). The early-Alpine metamorphic stage under coesite-eclogite facies conditions was overprinted by a pervasive late-Alpine greenschist-facies recrystallization. The BIU is sandwiched between the

overlying Rocca Solei Unit and the lower Pinerolo Unit; the small San Chiaffredo Unit is inserted between the BIU and the Pinerolo Unit.

- 4) The **Rocca Solei Unit** is also a portion of a pre-Alpine continental crust similar to the BIU and the San Chiaffredo Unit, consisting of a Variscan amphibolite-facies metamorphic basement (now garnet- and chloritoid bearing micaschist and micaceous gneiss, marble and eclogite; Matsumoto & Hirajima, 2000), intruded by Permian granitoids (now fine-grained orthogneiss and augen-gneiss with minor metagranitoid). The early-Alpine metamorphism under quartz-eclogite facies conditions was overprinted by a pervasive late-Alpine greenschist-facies recrystallization. The San Chiaffredo and Rocca Solei Units could be possibly the same unit repeated by folds. However, it seems highly unlikely that such geometry would allow to insert the UHP BIU in between, with a totally different exhumation history.

Suggested petrologic criteria for recognising the UHP BIU from the adjoining HP units

In order to distinguish tectonometamorphic units of continental crust that experienced polymetamorphic and polyphase overprints at different P - T conditions, the main problem derives from the fact that the latest tectonometamorphic events extensively obliterated the previous mineral assemblages and structures. This problem is very serious in quartz-rich continental crust that was exhumed after the HP metamorphism, because the HP minerals are strongly sensitive to decompression and are transformed very easily to low- P mineral assemblages, losing traces of the previous history. This problem may be partially overcome if micro-inclusions in minerals less sensitive to decompression, such as garnet, are examined in detail.

The general criteria listed below may be applied to similar metamorphic basement, i.e. to continental crust lithologies that experienced HP to UHP metamorphism. Figure 3 shows the main differences between UHP and HP assemblages in metagranitoid (Figs. 3a,b), eclogite (Figs. 3c,d) and metapelite (Figs. 3e,f) from the BIU and the overlying Rocca Solei unit, respectively. The petrologic criteria used to distinguish the UHP BIU from the adjacent HP units are the following:

(1) Presence of peculiar lithologies and mineral assemblages:

- (a) “whiteschist”, i.e. metasomatic rocks with granitoid protolith (see e.g., Compagnoni & Hirajima, 2001; Ferrando et al., 2009; Ferrando, 2012).
- (b) “Na-whiteschist”, metasomatic rocks with similar bulk rock chemical composition as the “whiteschist”, except for the presence of Na instead of K.

(2) Presence or lack of index minerals:

- (a) Coesite is found as armoured inclusions in minerals such as garnet (pyrope and almandine), clinopyroxene (jadeite and omphacite), kyanite, zoisite, and zircon. The coesite relics are often rimmed with palisade quartz or are totally replaced by polycrystalline quartz aggregates derived from coesite inversion, with radial cracks in the surrounding mineral, due to the volume increase connected to the coesite ($\delta=2.92$) - quartz ($\delta=2.65$) inversion (Figs. 3c, 4a,f).
- (b) Pyrope (Fig. 2b) with composition very close to that of the pure end-member (Prp_{80 to 98}) in the “whiteschist” (e.g., Ferrando et al., 2009).
- (c) Occurrence of other UHP index minerals, such as ellenbergerite (Fig. 4b), phospho-ellenbergerite, or magnesiodumortierite found as inclusions armoured in pyrope (Chopin & Ferraris, 2003).

- (d) Glaucophane with composition very close to that of the pure Fe-free end-member in rocks whose chemistry in the NMASH system approaches that of the “sodic whiteschist” (Kienast et al., 1991).
- (e) In metagranitoids, granoblastic polygonal quartz aggregate pseudomorphous after the former igneous quartz crystals (Figs. 2a, 3a, 4c), interpreted as evidence of the former presence of UHP coesite (Biino & Compagnoni, 1992).
- (f) The presence of aragonite instead of calcite in BIU marbles is not to be expected (e.g., Castelli et al., 2007; Groppo et al., 2007b) because of the high speed of the aragonite to calcite inversion at the relatively high-*T* of the BIU metamorphism.

(3) *Presence of peculiar mineral assemblages:*

- (a) Pyrope + coesite (or polycrystalline quartz aggregates as its inversion product) (Fig. 4a,d) instead of kyanite + talc in the “whiteschist” (e.g., Ferrando et al., 2009).
- (b) Kyanite + jadeite (Fig. 4e, f) instead of paragonite in orthogneiss of suitable composition.
- (c) Kyanite instead of paragonite in eclogite.
- (d) Eclogite with peak recrystallization *T* of ca. 730 °C instead of 500-550 °C of the nearby units (e.g., Groppo et al., 2007a).
- (e) Almandine + kyanite (Fig. 3e) instead of chloritoid + quartz (Fig. 3f) in metapelite of suitable composition (e.g., Groppo et al., 2006).
- (f) Grossular-rich garnet + rutile (+ phengite) instead of the lower-*P* assemblage titanite + clinozoisite in orthogneiss.

(4) *Peculiar compositions and micro-/nanostructures in minerals:*

- (a) Phengite with high celadonite (Si > 3.50 a.p.f.u.) and low paragonite (< 10 mol%) substitutions (e.g., Castelli et al., 2007; Groppo et al., 2007a).
- (b) Phengite with unstrained talc and quartz lamellae evident at high resolution transmission electron microscope (HRTEM) (Ferraris et al., 2000).

The application of these general criteria to the BIU and further detailed petrologic studies led to constraining not only its peak *P-T* conditions (e.g. Castelli et al., 2007; Groppo et al., 2007a and references therein) but also its prograde (e.g., Ferrando et al., 2009) and retrograde (e.g., Groppo et al., 2006) trajectories. It is interesting to note that since the BIU discovery (Chopin, 1984) the inferred peak *T* did not change, whereas the peak *P* progressively increased from about 3.3 GPa within the coesite stability field (e.g., Compagnoni et al., 1995) to about 4.3 GPa within the diamond stability field. Even though so far microdiamonds have never been found, the *P* increase of about 1 GPa has been inferred from both experimental petrology (Hermann, 2003) on representative BIU rocks and from a number of different geobarometers and thermodynamic modelling (e.g., Castelli et al., 2007; Groppo et al., 2007a). The lack of diamond may be explained with the sluggishness of the graphite-diamond reaction at the relevant peak *T*.

As a final remark, we would emphasize that this approach (largely based on petrologic, microstructural and minerochemical analyses) led to a novel, significantly more detailed division of otherwise monotonous tectonometamorphic units. Moreover, this approach can be usefully applied to all complex metamorphic terrains, and is thus worthwhile to be put besides classic geological mapping.

Software

The map database was built by ESRI ArcGIS 9, whereas the final map layout was assembled by Corel Draw 9. Photos were managed and compiled with Corel Photo Paint 9.

Acknowledgements

Fieldwork and laboratory work was supported by Italian Consiglio Nazionale delle Ricerche (C.N.R.), and Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Grant ex-40%). The authors thank B. Lombardo for helpful discussions both in the field and in the laboratory. S. Long, R. Schmitt and an anonymous reviewer are gratefully acknowledged for their careful and constructive reviews.

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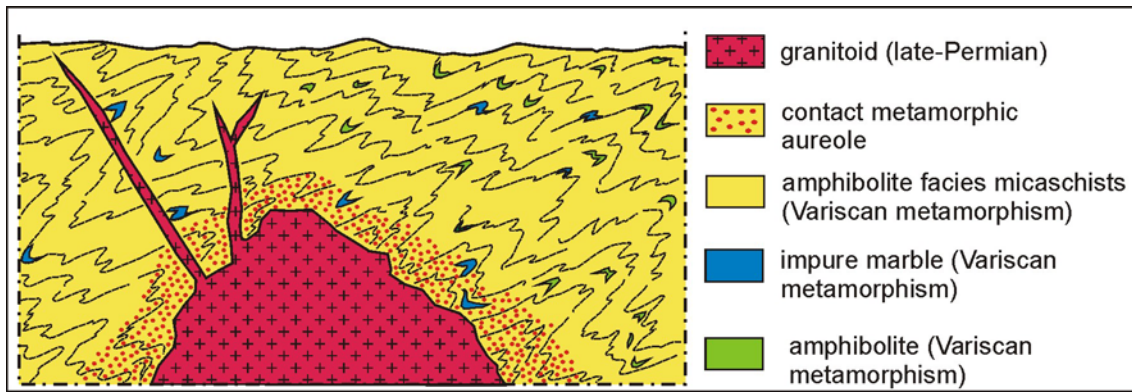


Fig. 1 – Schematic diagram representing pre-Alpine relationships among BIU lithologies as inferred from the few preserved structural and mineralogical relics that escaped the Alpine polyphase pervasive deformation.

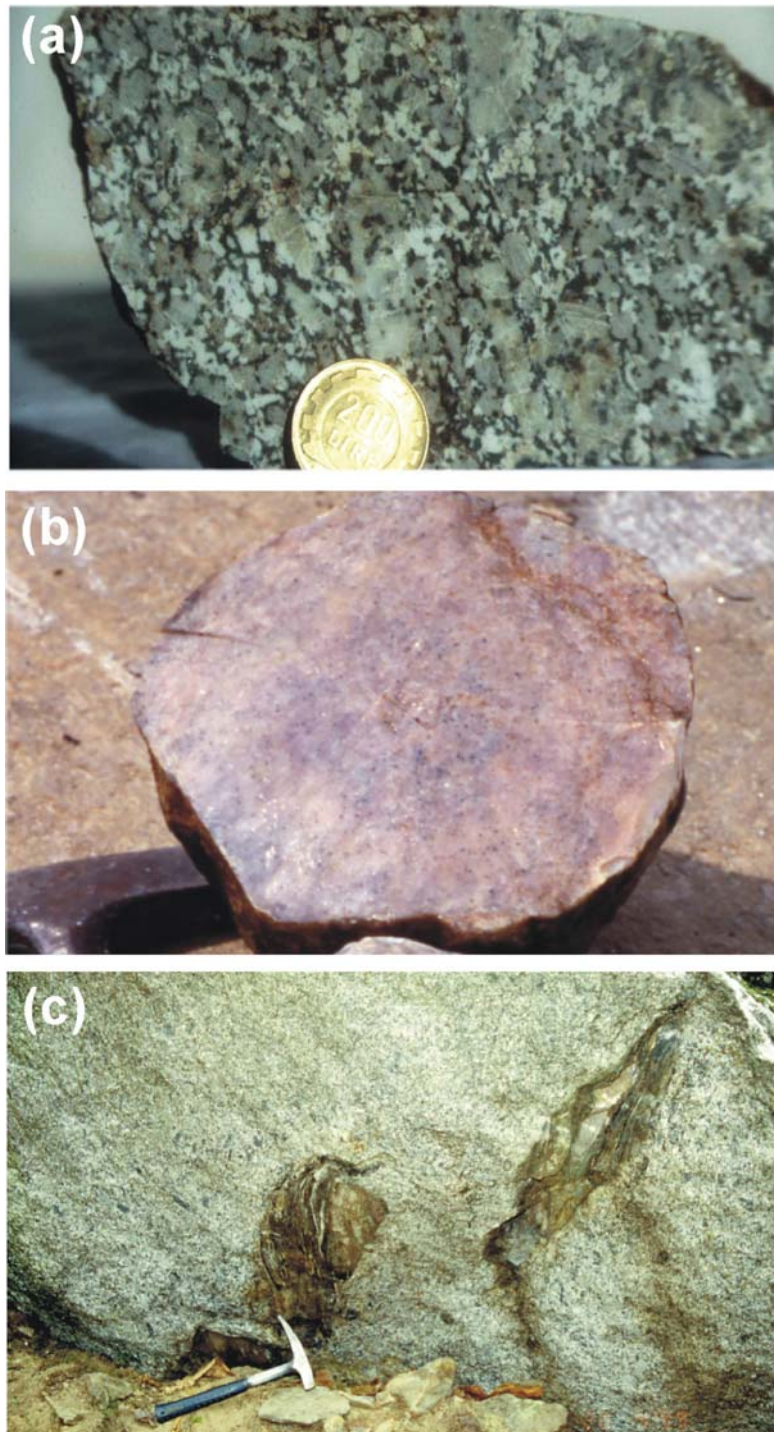


Fig. 2 – Representative BIU lithologies. **(a)** Relict late-Variscan metagranite of the Monometamorphic Complex. In hand specimen, the only evidence of the UHP metamorphic overprint is a poorly-developed foliation (roughly NS) and the sugary appearance of the original igneous quartz, now consisting of a granoblastic polygonal aggregate of metamorphic quartz, derived from inversion from former peak-*P* coesite (see also Figs. 3a, 4c). The coin is 20 mm across. **(b)** Pyrope megablast, ca. 20 cm across, from the whiteschist of the Monometamorphic Complex. The light pink garnet colour is due to its composition, very close to the pure pyrope end-member. Note that pyrope is crowded with inclusions of kyanite, rutile, etc. (see also Figs. 4a,b,d). **(c)** Marginal facies of the late-Variscan metagranite, crowded with contact metamorphosed xenoliths of the country Variscan paraschist. Note that the xenoliths preserve a clear Variscan metamorphic foliation. Case Bastoneri, Gilba valley.

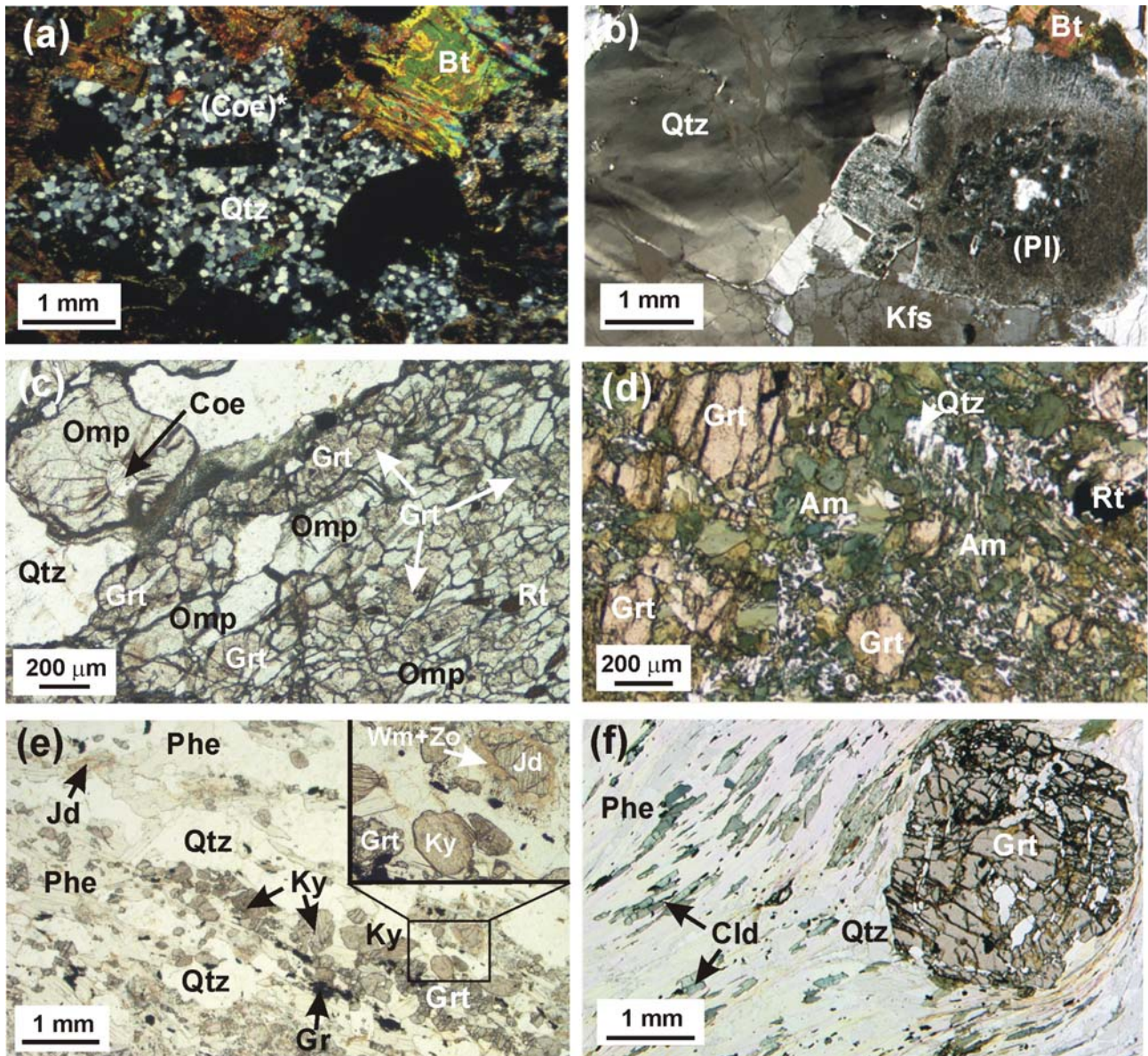


Fig. 3 – Representative microstructures and assemblages of metagranitoid, eclogite and metapelite from the UHP BIU and the overlying HP Rocca Solei Unit, as seen under optical microscope. **(a)** Metagranitoid from the UHP Brossasco-Isasca Unit. Note the fine grained granoblastic aggregate of quartz, statically derived from inversion of coesite which replaces the igneous quartz during UHP metamorphism. Sample DM496. Crossed Polars (XPL). Mineral abbreviations after Whitney & Evans (2010). **(b)** Metagranite from the HP Rocca Solei Unit. Note in the left portion of the photomicrograph a single grain of igneous quartz, with wavy extinction due to incipient deformation, which indicates that the rock did not experience pressures higher than the quartz upper stability. Sample DM 1513. XPL. **(c)** Fine-grained eclogite from the UHP Brossasco-Isasca Unit. Note in the upper left portion of the photomicrograph the coarse grained omphacite + quartz (after coesite) vein, and the coesite relic preserved within omphacite. The foliation is defined by preferred orientation of omphacite. Sample DM1586. Plane Polarized Light (PPL). **(d)** Eclogite from HP Rocca Solei Unit. Dark green retrograde edenitic to pargasitic amphibole replaces garnet and omphacite. Sample DM1497. PPL. **(e)** Metapelite from UHP Brossasco-Isasca Unit. The rock consists of quartz (after coesite), garnet, kyanite, jadeite, phengite and accessory rutile and graphite.

The kyanite-jadeite assemblage indicates that the rock experienced pressures higher than the upper paragonite stability. Sample DM689. PPL. (f) Metapelite from the HP Rocca Solei Unit. The rock consists of quartz, phengite, chloritoid, and garnet porphyroblasts. The presence of chloritoid + quartz points to low- T conditions and indicates that the rock did not experience UHP metamorphic conditions. Sample DM1504. PPL.

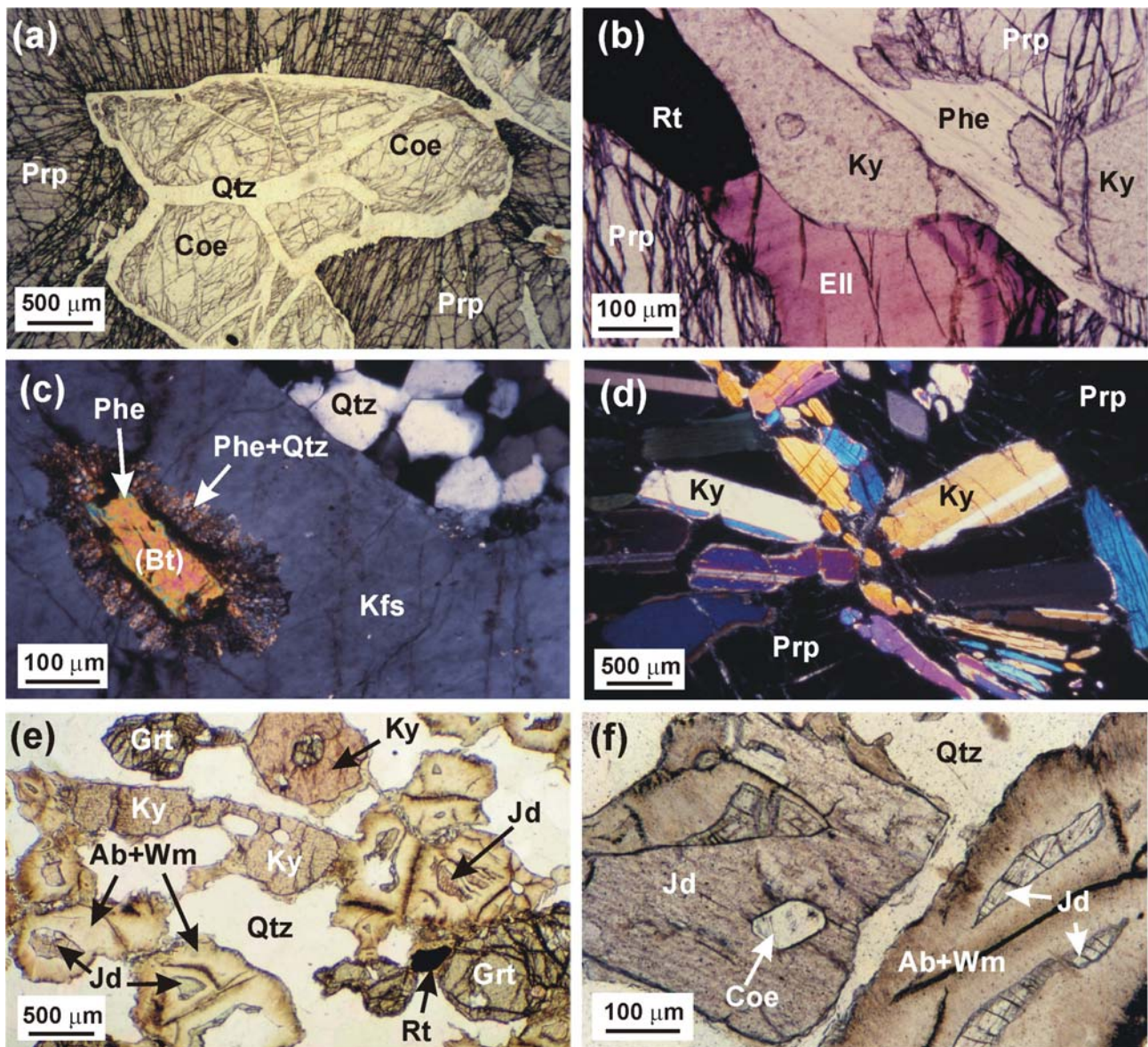


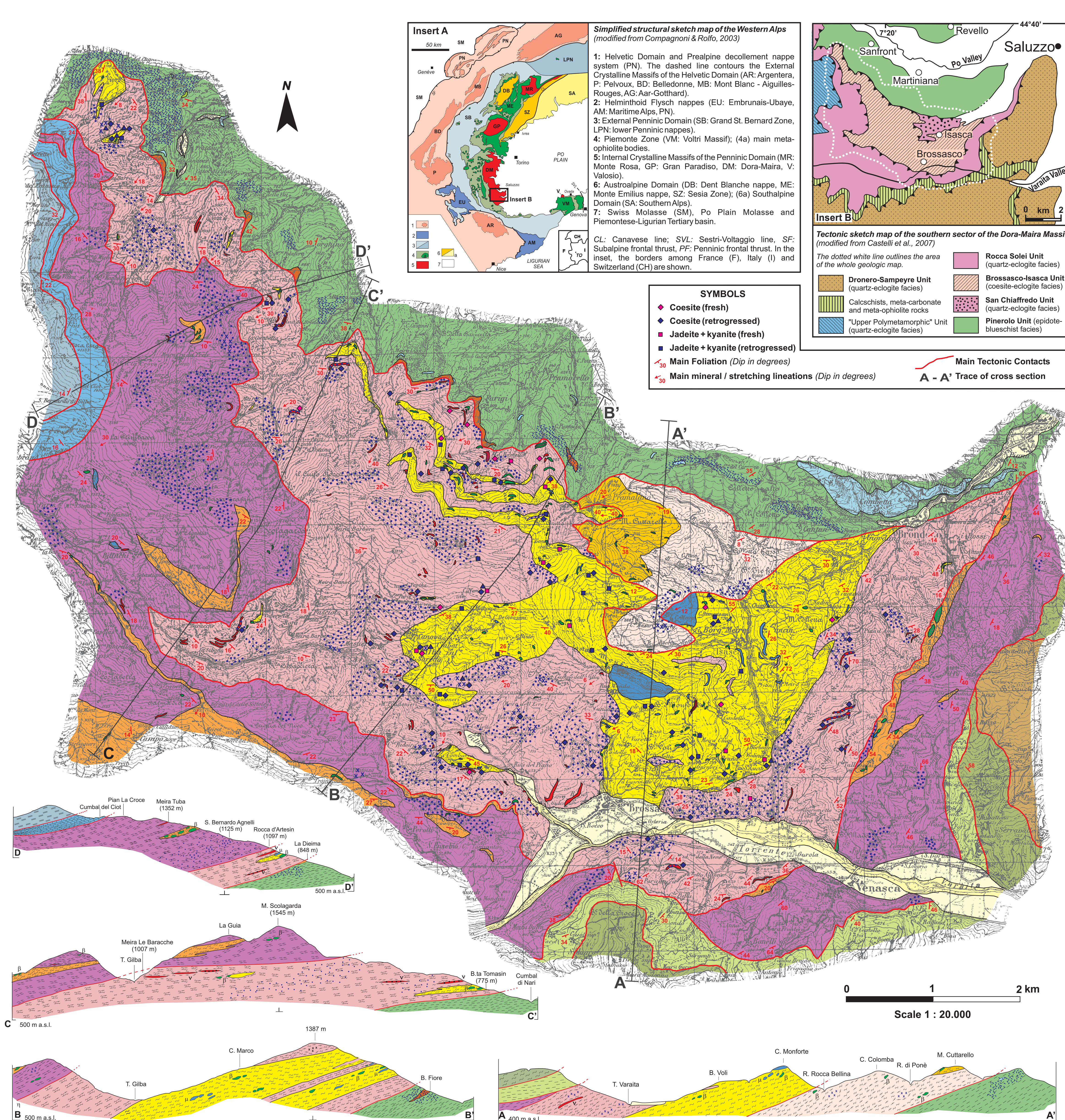
Fig. 4 – Representative index minerals and assemblages diagnostic of UHP metamorphism in the BIU. (a) Pyrope whiteschist. Relics of coesite, included in a pyrope porphyroblast, are partially converted to quartz along rims and fractures. Radial fractures, consequent to volume increase during the coesite to quartz inversion, are developed in the hosting pyrope. Sample DM507. PPL. (b) Zoned ellenbergerite in association with kyanite, phengite, and rutile armored in a pyrope megablast from a whiteschist. Ellenbergerite, a mineral so far reported only from the UHP BIU unit, is always preserved as inclusion. Sample DM450. PPL. (c) Detail of a metagranite, showing an igneous biotite included in a K-feldspar which is pseudomorphically replaced by a single phengite crystal and surrounded by a thin garnet corona and a dactylitic phengite + quartz intergrowth. In the upper right, a granoblastic polygonal quartz aggregate from former peak coesite, developed after primary igneous quartz. Sample DM 60. XPL. (d) Radial kyanite aggregate in pyrope (black) from whiteschist. Some pyropes contain more than 50 vol.% of mineral inclusions, kyanite largely prevailing. Sample DM450. XPL. (e) Garnet - jadeite - kyanite - quartz / (coesite) granofels. The presence of the jadeite + kyanite assemblage indicates that P conditions, higher than the paragonite breakdown, have been reached because of the reaction: $\text{Pg} = \text{Jd} + \text{Ky} + \text{H}_2\text{O}$. In the rock matrix, jadeite is pseudomorphically replaced by albite + white mica, and coesite by granoblastic quartz. (f) Garnet - jadeite - kyanite - quartz / (coesite) granofels. The presence of the jadeite + kyanite assemblage indicates that P conditions, higher than the paragonite breakdown, have been reached because of the reaction: $\text{Pg} = \text{Jd} + \text{Ky} + \text{H}_2\text{O}$. In the rock matrix, jadeite is pseudomorphically replaced by albite + white mica, and coesite by granoblastic quartz.

Sample DM442. PPL. (f) Coesite, partly inverted to quartz, included in a jadeite from a kyanite - jadeite - quartz / (coesite) granofels. Jadeite is mostly retrogressed to albite + white mica. Sample DM442. PPL.

GEOLOGICAL MAP OF THE UHP BROSSASCO - ISASCA UNIT (WESTERN ALPS)

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The Geological Map of the UHP Brossasco-Isasca Unit was compiled from geological surveys by R. Compagnoni, T. Hirajima, F. Rolfo and R. Turello (1987-1994), and C. Groppo (2001-2004).
The topographic map derives from the 1:25,000 maps of the IGM (Istituto Geografico Militare), tavolette: 079 I-NO (Sanfront), 079 I-NE (Revello), 07-I-SO (Melle) and 079 I-SE (Venasca).